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BICMOS BANDGAP REFERENCE WITH POLINOMIAL CURVATURE CORRECTION

Cosmin Popa

University Politehnica of Bucharest,
B^dul Iuliu Maniu 1-3, Bucuresti, Romania
email: cosmin@golana.pub.ro

Abstract: *A bandgap voltage reference with a circuit providing compensation of the curvature is described. The temperature nonlinearity of the base-emitter voltage is compensated by polarising a bipolar transistor at a collector current , which is a polynomial function on temperature. Theoretical calculations show that the thermal instability of the output voltage can be strongly reduced by this technique. The curvature-corrected bandgap voltage reference is implemented in a 0.35 μ BiCMOS technology and presents a very small temperature coefficient (2ppm/K), confirmed by the SPICE simulation, based on the mentioned technology model parameters.*

Keywords: Bandgap voltage reference, temperature coefficient, curvature-correction

1. INTRODUCTION

Reference voltage generators are used in many analog or digital applications such as A/D and D/A converters, acquisition data systems or memories. The voltage references are required to be stabilized over process, supply voltage and, especially, temperature variations and also to be implemented without modification of the fabrication process.

The bandgap reference (BGR) is one of the most popular reference voltage that successfully meets these requirements. Bandgap references add a forward bias voltage across a pn diode with a voltage that is ProporTional to Absolute Temperature (PTAT) to produce an output that is insensitive to changes in temperature.

The output voltage of a bandgap reference is based on the bandgap energy E_G, a well defined, in a first-order analysis temperature independent physical value [1].

Resulting from the previous principle, the temperature coefficient of the classic bandgap reference is theoretical limited at a relatively large value of about hundred ppm/K, unacceptable for increased performanmces circuits that require a much smaller sensitivity of the reference voltage with respect to the temperature.

In order to improve the bandgap reference temperature coefficient, two different principial methods have been developed: the ***linearisation of the base-emitter voltage*** temperature dependence by a suitable polarisation of the bipolar transistor [2], [3] and the ***compensation of the nonlinearity of the base-emitter voltage*** by a correction voltage which is added to the bandgap voltage reference, or by a correction current, summed with the PTAT current from the basic bandgap reference [4], [5], [6].

This paper presents a base-emitter voltage nonlinearity compensation by using a voltage drop on the resistor, which is a polynomial function on absolute temperature. The temperature coefficient obtained by this technique meets two fundamental alternative goals of bandgap voltage references: a very small value for a limited temperature range or a medium value for an extended temperature range. The pnp vertical transistors were prefered to other voltage sources with a negative temperature dependence (based on the threshold voltage or carriers mobility temperature dependence) because of the much better stability.

2. THEORY AND ANALYSIS

2.1. The basic bandgap reference

The basic circuit of a bandgap voltage reference is presented in Figure 1.

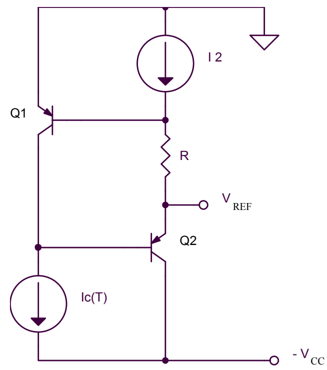

Figure 1: The basic circuit of the bandgap voltage reference

Supposing that the bipolar transistor is polarised at a collector current $I_C(T)$ independent on temperature, the reference voltage and the temperature coefficient of the reference voltage will have the following expressions [1]:

$$V_{REF}(T) = 3V_t\left[1+\ln\left(\frac{T_0}{T}\right)\right]+E_G \quad (1)$$

$$TC_{V_{REF}}(T) = \frac{3K}{q}\ln\left(\frac{T_0}{T}\right) \quad (2)$$

where T_0 is the reference temperature, V_t is the thermal voltage and E_G is the silicon bandgap energy. So, because the reference voltage is a sum of a PTAT voltage and a base-emitter voltage with a negative nonlinear temperature characteristic, in order to improve the temperature behaviour of the bandgap reference, it is necessary to develop a circuit technique which must cancel the main base-emitter voltage temperature nonlinearities.

The temperature dependence of the base-emitter voltage will be given by [2]:

$$V_{BE}(T) = \frac{T}{T_0}\left[V_{BE}(T_0) - E_G(T_0)\right] + E_G(T) + \frac{KT}{q}\ln\left[\frac{I_C(T)}{I_C(T_0)}\right] - \eta\frac{KT}{q}\ln\frac{T}{T_0} \quad (3)$$

where T_0 is the reference temperature, η is a constant which depends on the technological process and E_G is the silicon bandgap energy temperature with the following temperature dependence [6]: $E_G(T) = a - bT - cT^2$, a, b and c being supposed to be temperature-independent constants equal with $a = 1{,}1785V$, $b = 9{,}025\times10^{-5}V/K$ and $c = 3{,}05\times10^{-7}V/K^2$. From the previous two relations, expanding the base-emitter voltage in polynomial series and supposing that the bipolar transistor is working at a collector current $I_C(T)$ linear dependent on temperature, it results:

$$V_{BE}(T) = V_{BE}(T_0) + \sum_{k=1}^{\infty} a_k (T - T_0)^k \quad (4)$$

where $a_k, k = 1 \div \infty$ are the constant coefficients of the expansion, with the following expressions: $a_1 = [V_{BE}(T_0) - E_G(T_0)]/T_0 - b - 2cT_0 - (\eta - 1)K/q$; $a_2 = (\eta - 1)K/2qT_0 - c$; $a_3 = -(\eta - 1)K/2qT_0^2$; $a_4 = (\eta - 1)K/3qT_0^3$; ….. .

Considering that the I_2 current is temperature dependent and its Taylor expansion around T_0 is $I_2(T) = \sum_{k=0}^{\infty} b_k (T - T_0)^k$, where $b_k, k = 1 \div \infty$ are the constant coefficients of I_2 current expansion, the reference voltage will be given by:

$$V_{REF}(T) = V_{BE}(T_0) + b_0 R + \sum_{k=1}^{\infty} (a_k + b_k R)(T - T_0)^k \quad (5)$$

So, because of the nonzero values of the coefficients $a_k + b_k R, k = 1 \div \infty$, the temperature behaviour of the basic bandgap reference from Figure 1 will be rather poor, justifying the necessity of a curvature-correction implementation.

2.2. The curvature-corrected bandgap reference

The curvature-corrected bandgap reference is presented in Figure 2. The proposed idea is to introduce small controlable nonlinearities in the expression of I_2 current, with oposite values to those of base-emitter voltage. In this way, the main reference voltage nonlinearities will be cancel out, remaining only the superior-order harmonics in the output voltage temperature characteristic. The result will be a much smaller value of the temperature coefficient of the curvature-corrected bandgap reference.

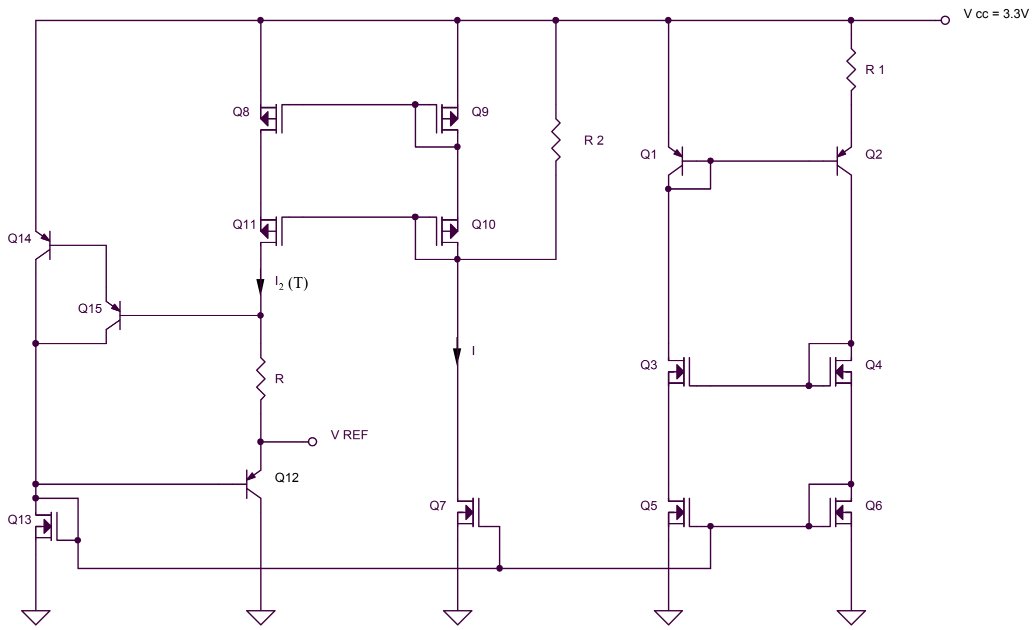

Figure 2: The bandgap voltage reference with polynomial curvature correction

The reference voltage of the circuit from Figure 2 is given by $V_{REF}(T) = -2V_{BE}(T) - RI_2(T)$ and the Taylor expansion of the reference voltage is expressed by:

$$V_{REF}(T) = -2V_{BE}(T_0) - b_0 R - \sum_{k=1}^{\infty}(2a_k + b_k R)(T - T_0)^k \tag{6}$$

In order to obtain a voltage reference very stable with respect to the temperature variations, it is necessary to cancel the error terms from expression (6) ($2a_k + b_k R, k > 1$), especially the quadratic term, which has the more important ponder in the non-linearity of the base-emitter voltage (the first-order term, $2a_1 + b_1 R$ was already cancelled in the first-order analysis). The circuit proposed in Figure 2 realizes this feature by using a non-linear temperature dependence of the current $I_2(T)$ through resistor R. MOS transistors have the following aspect ratio: $(W/L)_3 = ... = (W/L)_{11} = 10\mu / 0.3\mu, (W/L)_{13} = 100\mu / 0.3\mu$ and the resistors values are: $R = 1.2K\Omega$, $R_1 = 100\Omega, R_2 = 55K\Omega$.

Obtaining the current $I_2(T)$

The current divider Q_9, Q_{10} and R_2 let obtain small controllable nonlinearities in the expression I_2 of the output current. Because of the strong temperature dependence of the carriers mobility, given by $\mu_p(T) = \mu_P(T_0)(T_0 / T)^2$, the expression of current I_2 could be written, as a temperature function:

$$I_2(T) = f(T) = \frac{C_1 T}{R_2 + C_2\sqrt{T}} \tag{7}$$

where C_1 and C_2 are two temperature-independent constants with the following expressions: $C_1 = (K/q)\ln(m)$, $C_2 = \sqrt{2q/[\mu_p(T_0)T_0^2 C_{ox}(W/L)_{9,10} K \ln(m)]}$.

The main coefficients $b_k, k = 0 \div 3$ of the $I_2(T)$ expansion are:

$$b_0 = \frac{C_1 T_0}{R + C_2\sqrt{T_0}}\,;\; b_1 = \frac{C_1 R + \frac{C_1 C_2 \sqrt{T_0}}{2}}{\left(R + C_2\sqrt{T_0}\right)^2}\,;\; b_2 = -\frac{C_1 C_2}{8}\frac{\frac{3R}{\sqrt{T_0}} + C_2}{\left(R + C_2\sqrt{T_0}\right)^3} \tag{8}$$

So, the condition of cancelling the second-order harmonic from the expression (6) of the reference voltage is $2a_2 + b_2 R = 0$, which could be fulfilled by design compulsions. In this case, the remaining temperature dependence of the reference voltage will be given only by superior-order harmonics from expression (6), for $k \geq 3$, with a much smaller ponder in the temperature behaviour of the voltage reference than the second-order distortion that was just cancelled.

3. EXPERIMENTAL RESULTS

The circuit was implemented in 0.35μ BiCMOS technology. The SPICE simulation of the basic voltage reference from Figure 1 shows a relative large temperature coefficient, about $33 ppm/K$ for an usual choice of the limited temperature range, $263K < T < 308K$.

The SPICE simulation $V_{REF} = V_{REF}(T)$ of the curvature-compensated voltage reference is presented in Figure 3 (a - for extended temperature range and b - for limited temperature range).

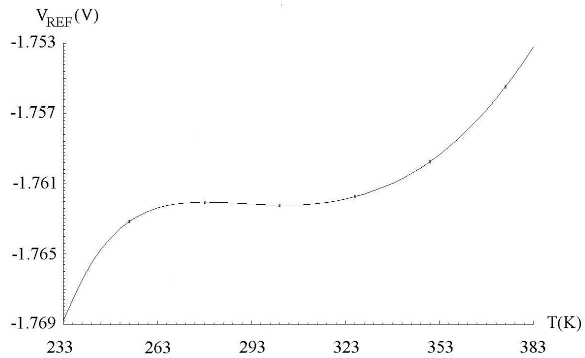

Figure 3a: SPICE simulation $V_{REF} = V_{REF}(T)$ of the curvature-compensated voltage reference for extended temperature range

Considering the limited temperature range $263K < T < 308K$ (Figure 3b), the temperature coefficient of the improved bandgap reference from Figure 2 is decreasing to $2.15 ppm$. The temperature range with small thermal coefficient could be shifted right or left by a suitable choice of the constants C_1 and C_2. So, in order to obtain a good temperature behaviour, the optimal designed temperature range could be superposed on the chip ambient temperature range with the result of decreasing the temperature coefficient of the curvature-corrected bandgap reference for this temperature domain.

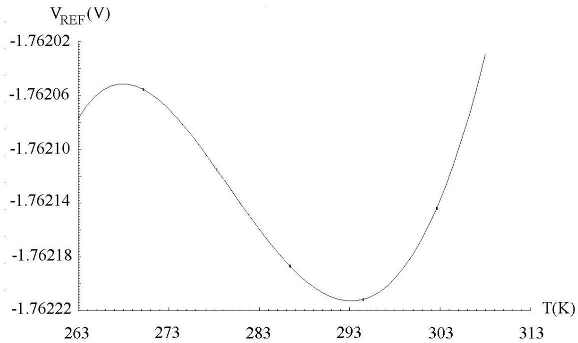

Figure 3b: SPICE simulation $V_{REF} = V_{REF}(T)$ of the curvature-compensated voltage reference for limited temperature range

4. CONCLUSIONS

Because of the temperature dependence of the base-emitter voltage, the well-known method used to obtain an improved performances bandgap reference is the linearization of $V_{BE}(T)$ temperature dependence by polarizing the bipolar transistor at a collector current which is a particularly function on temperature. This paper proposes a new technique based on the compensation of the nonlinearity of the base-emitter temperature dependence with a voltage, which is polynomial dependent on temperature. The SPICE simulation of the circuit realized in 0.35μ BiCMOS technology confirms the theoretical results (a temperature coefficient about $2\ ppm/K$).

5. REFERENCES

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